

IMPERIAL INSTITUTE

MONOGRAPHS ON MINERAL RESOURCES
WITH SPECIAL REFERENCE TO THE
BRITISH EMPIRE

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IMPERIAL INSTITUTE

MONOGRAPHS ON MINERAL RESOURCES
WITH SPECIAL REFERENCE TO THE
BRITISH EMPIRE

PREPARED UNDER THE DIRECTION OF THE
MINERAL RESOURCES COMMITTEE OF THE
IMPERIAL INSTITUTE WITH THE ASSISTANCE
OF THE SCIENTIFIC AND TECHNICAL STAFF

COBALT ORES

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WITH A MAP



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IMPERIAL INSTITUTE

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GENERAL PREFACE

THE Mineral Resources Committee of the Imperial Institute has arranged for the issue of this series of Monographs on Mineral Resources in amplification and extension of those which have appeared in the *Bulletin of the Imperial Institute* during the past fifteen years.

The Monographs are prepared either by members of the Scientific and Technical Staff of the Imperial Institute, or by external contributors, to whom have been available the statistical and other special information relating to mineral resources collected and arranged at the Imperial Institute.

The object of these Monographs is to give a general account of the occurrences and commercial utilization of the more important minerals, particularly in the British Empire. No attempt has been made to give details of mining or metallurgical processes.

HARCOURT,
Chairman Mineral Resources Committee.

IMPERIAL INSTITUTE,
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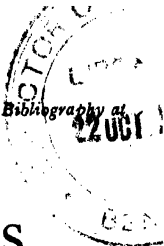
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COBALT ORES

CHAPTER I

COBALT ORES: THEIR OCCURRENCE, CHARACTERS AND USES

INTRODUCTION

ALTHOUGH the metal cobalt was prepared for the first time in the eighteenth century, blue cobalt glass has been known from time immemorial, having been found in the tombs of the ancient Egyptians and in the ruins of Troy [1/p. 417].

The word "cobalt" occurs in the writings of Paracelsus and Basil Valentine to denote a goblin supposed to haunt a mine, from the German *Kobald*, an evil spirit. The term during the Middle Ages was also applied to "false ores," or ores which did not yield metals by the processes then in vogue. Afterwards it was confined to the minerals used for producing a blue colour in glass. In 1735 G. Brandt stated that the blue colouring principle is due to the presence of a metal which he called "cobalt rex," hence our "cobalt" [2] [3].

The compounds of cobalt have been known and used for many years in the ceramic industry, for the production of blue glass, and as smalt and other pigments; but the metal itself has only come into industrial use in comparatively recent years. Even to-day it is only sparingly used, not because it lacks utility, but because its price is high compared with that of nickel, which in most respects fulfils the same functions.

While nickel and cobalt may be regarded as interchangeable for many purposes, cobalt has been found to possess valuable properties peculiar to itself: for instance that of forming a unique and valuable series of alloys, with chromium as the

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other main constituent, which alloys are in somewhat extensive use as a substitute for high speed steel [4/pp. 397-401].

As compared with nickel for electroplating, cobalt has been found to possess certain advantages (*see* p. 16).

Metallic cobalt has many possible uses, but its more general employment in the arts and industries depends upon its cheaper production, the prospects for which are not hopeful. The known deposits of cobalt ore are relatively small and the percentage of the metal in such ores is usually quite low. Frequently its extraction can only be economically considered when it is a by-product in the recovery of the more valuable associated metals, such as silver. The extraction of cobalt from such mixed ores is also complicated and costly, so much so, that it is apparently often considered preferable to allow it to go to waste rather than to attempt its recovery as a by-product [5/p. 41]. For these reasons it seems probable that the use of cobalt will continue to be restricted to special purposes for which a cheaper metal cannot satisfactorily be substituted. On the other hand, such particular purposes may well become more widely developed, and there is also the further possibility of the discovery of new uses for cobalt. The Canadian Department of Mines has caused researches to be made with a view to extending the uses of cobalt. These researches have already widened the field for the profitable employment of the metal and certain of its alloys [6] [7] [8].

ORE MINERALS OF COBALT

The chief ore minerals of cobalt are *Smaltite*, *Cobaltite*, *Linnæite*, *Glaucodot*, *Erythrite* and *Asbolite*. Some of their properties according to Dana are given in the following table :

Type.	Name.	Cobalt content.	Formula.	Specific gravity.	Hardness.
		%			
Arsenide	Smaltite	28.2	CoAs_2	6.4-6.6	5.5-5.6
Sulpharsenide	Cobaltite	35.5	$\text{CoS}_2 \cdot \text{CoAs}_2$	6.0-6.3	5.5
Sulphide	Linnæite	57.9	$\text{CoS} \cdot \text{Co}_2\text{S}_3$	4.8-5.0	5.5
Sulpharsenide	Glaucodot	15-24.77	$(\text{CoFe})_2\text{AsS}$	5.9-6.01	5.0
Hydrous					
Arsenate	Erythrite	29.4	$\text{Co}_3\text{As}_2\text{O}_8 \cdot 8\text{H}_2\text{O}$	2.9	1.5-2.5
Oxide	Asbolite	up to 32	Uncertain	Varied	Varied

Smaltite, or *grey cobalt ore*, is the principal mineral. It is found, and has been worked, at Freiberg, at Annaberg, and at Schneeberg in Saxony; at Joachimsthal, in Bohemia; and is also one of the chief cobalt minerals at Cobalt, Ontario.

Cobaltite, or *cobalt glance*, is more widely distributed than smaltite, with which it is frequently associated. It is the chief mineral of the cobaltiferous ores of Sweden, Norway, and Rajputana in India, and is a common mineral of the deposits of Cobalt, Ontario.

Linnæite, sometimes known as *cobalt pyrites*, is less common than either of the above, but it has been mined in various places in Europe, and is a source of the by-product cobalt obtained from copper and lead ores in Missouri.

Glaucodot is found near Huasco, Atacama, Chile, and at Hokanbol, Sweden.

Erythrite, or *cobalt bloom*, is an oxidation product of the arsenide ores, and is therefore found in the weathered outcrops of these ores. It is often present as a conspicuous crimson-coloured substance, and thus serves as a valuable indicator of mineral outcrops containing cobalt.

Asbolite, *asbolan*, or *cobaltiferous wad*, is a mixture of manganese and other metallic oxides of uncertain composition. Its occurrences are fairly common, and it has been found in many parts of the world, including Cheshire in England, and elsewhere in Europe. It is the principal ore mineral of New Caledonia, formerly the world's chief producer.

The following minerals of cobalt are unimportant:

Willyamite, $\text{Co}_2\text{NiS}_2\cdot\text{CoSb}_2\text{NiSb}_2$, a somewhat rare mineral found at Broken Hill, New South Wales: it is a variety of *ullmannite*, $\text{NiS}_2\cdot\text{NiSb}_2$.

Skutterudite, CoAs_2 , found at Skutterud, near Modum, Norway.

Bismutosmaltite, Co(AsBi)_2 , a similar mineral, except that part of the arsenic is replaced by bismuth. It is one of the numerous minerals found in the Schneeberg district of Saxony.

Roseelite, $(\text{CaCoMg})\text{As}_2\text{O}_8\cdot 2\text{H}_2\text{O}$, and *sphaerocobaltite*, CoCo_2 , a complex arsenate and carbonate respectively of cobalt, oxidation products of the Schneeberg ores, and *Remingtonite*,

a hydrous carbonate of uncertain composition, found only at Finksburg in Maryland, United States.

Safflorite, CoAs_2 , which has the same composition as smaltite, and is found associated with that mineral at Schneeberg and some other places.

Alloclasite, a glaucodot in which bismuth has taken the place of iron. It is uncommon, and is reported to occur at Oravicza in Rumania.

Cobalt in small quantities is often associated with nickel ores both of the pyrrhotite and silicate types, and is sometimes found accompanying arsenopyrite.

Metallic cobalt has also been reported as a constituent of some meteorites, and its presence has been detected in the sun [2].

COBALT ORE DEPOSITS

Cobalt ore deposits are widely distributed, but in a few cases only are they of immediate commercial value.

The known occurrences in the United Kingdom are of little significance, but in the cobalt ore deposits of Ontario, the British Empire possesses what has now become the most important source of the metal in the world. Even in this case, however, the cobalt contents of the ore are of secondary importance, the deposits being primarily worked for silver.

The cobalt contained in the ores shipped from 1907 to 1912 amounted to 5,961 tons [9/p. 35], or an average of about 1,000 tons per annum, yet at the end of that period the world's consumption was estimated at only 300 tons of cobalt oxide annually [9/p. 41].

The only other deposits of cobalt ore within the Empire, which have possessed considerable importance, are those of New South Wales, from which an appreciable output was recorded prior to the discovery of the Ontario deposits [9/p. 225]. Production, however, ceased some years ago.

Cobalt ore deposits in territory other than British include those of Germany situated at Schneeberg and Annaberg. These deposits, which were being worked for cobalt over 300 years ago, have yielded relatively large quantities of cobalt ore, but the recent production has been on quite a small scale.

The most important foreign cobalt ore deposit is that of the island of New Caledonia. For some years preceding the opening up of the Ontario deposits it was the source of the greater portion of the world's requirements of cobalt, but production has now, apparently, either ceased entirely or become quite small [6/p. 14].

Austria, Norway and Sweden were formerly amongst the countries producing cobalt, but no production has been recorded for many years past.

Cobalt ore deposits may be divided into two groups. In one of these, the ore occurs in distinct vein formations, the mineralization of which is complex, and includes economic minerals to which the cobalt is often subordinate, both in quantity and value. The other group includes concentrations by surface agencies of decomposition products of weathered and altered basic igneous rocks, such as serpentized dunites or peridotites.

In this latter case, the primary igneous rock is generally believed to be the source of the cobalt compounds, but with regard to the cobalt found in vein formations the origin is less certain. Such veins have been found in various kinds of rock, including crystalline limestones, clay-slates, conglomerate, quartzite, schists, and rocks of a shaly character. These enclosing rocks afford no clue to the origin of the cobalt, and its source must therefore be sought in other directions. The characters of these vein deposits and of the associated gangue and other minerals indicate a thermal origin, and the cobalt, nickel and some other minerals have probably been carried by, and deposited from, waters ascending from a considerable depth, that is to say, magmatic waters. This view is supported by the fact that cobalt-bearing veins are almost without exception in the immediate vicinity of intrusive igneous rocks, and in a number of cases are contained in the intrusive body itself. The rich veins of cobalt-silver ores in Ontario well illustrate these conditions. While the majority of these veins are in the contact rocks, a number of the productive veins occupy fissures in a dolerite¹ intrusive. In this case it is con-

¹ Diabase of Canadian geologists.

sidered by W. G. Miller that the dolerite eruptive and the cobalt minerals came from the same magma [9/p. 8].

The deposition of minerals in veins of this type has, however, been proved to have proceeded in two or more stages, different minerals being deposited at each stage. This introduces the possibility of more than one source for the various mineral constituents of these veins, and suggests that both magmatic and meteoric waters may have been instrumental in forming the ore-bodies.

In most cases, and particularly in outcropping ore-bodies, the primary deposition of the ore minerals has been altered by surface agencies in the superficial zone, and secondary minerals such as erythrite have been formed.

MINING OF COBALT ORES

The practice in mining cobalt ores necessarily varies with the character of the deposit and the enclosing rocks, but the methods adopted on the Cobalt field, Ontario, indicate the ordinary practice in mining deposits of that character. The mineral veins containing cobalt and other minerals are usually narrow, more or less vertical and short in length, and therefore somewhat costly to mine. Moreover certain of the veins are "blind," that is they do not reach the surface, necessitating a good deal of exploratory work in the shape of drives and crosscuts. It is stated that about one-half of the underground work is of a prospecting or exploratory character [9/p. 253].

In the early years of mining, the ore was obtained from narrow open cuts on the veins, the phenomenal richness of the ores in silver making the returns very high.

To-day the development and mining are carried out by the more systematic method of sinking shafts on or near the veins, and driving from these shafts along the veins so far as the ore is payable. Stations are cut at the shafts at 75 to 100 ft. intervals in depth, and it is from these that the drives are started. From the drives the ore is stoped by the overhand method; timbers being placed above to carry the broken ore, which is drawn off through the chutes placed about 30 to 45 ft. apart.

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Subsequent mining is carried out on the shrinkage system. Owing to the narrowness of the veins a quantity of wall rock is often mined to give room for working. Sometimes this rock is impregnated with sufficient mineral matter to make it worth treatment; otherwise it is separated by sorting. The fact that the veins are approximately vertical and the walls are of solid rock makes mining safe and serious accidents are rare [9/p. 253].

The mining of cobalt in New Caledonia is quite different in its character. Here the deposit is a superficial one. The cobalt mineral is asbolite, which is found in association with serpentine, considered to be the parent rock. This serpentine is more or less broken down by weathering, forming comparatively loose or slightly coherent material. The payable ore is first located and defined by sinking pits; the overburden, if any, is removed, and the cobalt-bearing serpentine is then picked down, the cobalt ore being separated by hand-sorting.

CONCENTRATION OF COBALT ORES

Cobalt ores, however carefully hand-sorted, contain much barren rock, and, on the other hand, the sorted poorer ore may contain valuable material.

Most of the mines on the Cobalt field, Ontario, supplement hand-sorting by wet gravity methods of concentration and, latterly, flotation methods have been used in combination with the wet gravity methods with results said to be satisfactory.

The wet gravity methods as practised are somewhat elaborate. After crushing the ore coarsely in jaw crushers and more finely in gyratory crushers or rolls, the product is passed through trommel screens, which divide it into (1) comparatively coarse material, which is jigged, and (2) fine material which goes to the classifiers. The jig tailing and the coarser portion from the classifiers are ground fine in a Chilian mill or by stamps and are classified again into sand and slime. The slime goes to a thickening tank and the thickened product to

vanners and canvas tables. The sand from the classifiers is treated on some form of sand concentrating table, and the middling from this on a second table. The tailing from both tables is rejected, and the concentrated material is further treated by tube milling, the resulting slime being passed over slime tables and finally over canvas tables. The coarser material from the second classifications is also treated on sand tables and afterwards on canvas tables.

The average recovery of the silver content from the concentrate is said to be about 80% [9/p. 257]; some portion of the 20% not so obtained is possibly recoverable by flotation methods, but no particulars are published.

The concentration of cobalt ores of the type obtained from New Caledonia cannot be effected by wet gravity or flotation methods, but the hand-sorted ore can be further concentrated to a matte in a blast furnace in the same way that nickel matte is produced.

METALLURGY OF COBALT

The metallurgical treatment of Canadian cobalt ores is by no means simple, involving as it does the recovery of the contained silver, cobalt, nickel, arsenic and small quantities of copper. The primary consideration is the recovery of the silver as the most valuable constituent of the ore, that of the other constituents being subordinate.

Three Canadian companies were operating refineries at a recent date, the Coniagas Reduction Co., Ltd., with works near Thorold; the Deloro Smelting and Refining Co., with works at Deloro; and Metals Chemical, Ltd., with works at Welland. Other small reduction plants work intermittently, and hitherto also a considerable proportion of the concentrated ore obtained from the cobalt mines has been taken by United States refineries (*see* p. 47).

The different concentrates vary in value, but the following are typical assays of ores and mill products received at the works of the Deloro Smelting and Refining Co. up to 1915 [6/p. 39]:

Analyses of Different Products at Deloro

	Ore (hand-picked).	Jig product.	Table concentrate.	Slime.
Silver . oz. per short ton	2,194	1,442	1,426	324
Cobalt %	7.90	10.40	8.20	2.10
Nickel "	4.30	5.80	3.80	0.50
Copper "	0.10	0.20	0.25	—
Iron "	5.00	6.50	11.60	6.80
Arsenic "	30.20	47.20	37.10	10.00
Sulphur "	1.70	3.70	8.25	2.98
Silica (SiO ₂) "	4.17	4.50	9.50	58.30
Lime (CaO) "	15.00	5.20	—	2.50
Magnesia (MgO) "	2.70	0.80	—	1.92

At Deloro the crushed ore is mixed with the necessary fluxes in a pug-mill and smelted in a low pressure blast furnace, with the production of slag, speiss, and crude silver bottoms. The speiss is crushed, calcined in coal-fired reverberatory furnaces or oil-fired Bruckner furnaces, and then given a chloridizing roast. The roasted material is then sent to agitation tanks, and the silver is there extracted by sodium cyanide solution, from which it is precipitated by aluminium dust. The crude silver bottoms obtained from the blast furnace are heated in an oxidizing atmosphere in oil-fired cylindrical rotary furnaces, the impurities being thus oxidized and to a large extent eliminated. The silver is further refined by being mixed with the precipitated silver from the cyanide solution, and is fused with nitre and borax in an oil-fired furnace and cast into bars. The arsenic is recovered as arsenious oxide in the flues and bag-houses connected with the blast furnace. When a high degree of purity is desired, the material is resublimed.

The principal impurities of cobalt ores are arsenic, iron and copper. When a solution containing nickel, cobalt and the above impurities is neutralized with ground calcium carbonate, the iron and arsenic combine to form ferric arsenate, FeAsO₄, a light-brown, flocculent to granular precipitate. Practically all the arsenic can be removed in this way, as well as all the copper, provided the latter be present only in small amounts—if present in large quantity, it must be removed by iron plates, or by electrolytic methods. Calcium hypochlorite (bleaching

powder) is then added to the solution containing cobalt and nickel, by which black hydroxide of cobalt, $\text{Co}(\text{OH})_2$, is precipitated. The latter is removed, and the precipitation of the remaining cobalt is continued, a quantity of black nickel hydroxide, $\text{Ni}(\text{OH})_2$, being precipitated at the same time. This intermediate precipitation produces mixed oxides, which must be retreated to produce pure cobalt and nickel oxides. The nickel left in solution is precipitated as nickelous hydroxide or hydrated carbonate by the addition of a solution of lime or sodium carbonate [6/p. 36].

H. T. Kalmus [10] investigated for the Department of Mines of Canada the reduction of the oxide of cobalt to metal, using as reducing agents: (1) carbon in the form of anthracite, (2) hydrogen, (3) carbon monoxide in the form of producer gas, and (4) aluminium powder. Of these methods (1) and (3) are the most favourable from an economic standpoint, but (2) is useful for producing a chemically pure cobalt and (4) is a rapid and easy way of preparing small quantities of cobalt metal free from carbon.

PHYSICAL PROPERTIES OF COBALT

The physical properties of cobalt, not previously extensively investigated, have been the subject of a series of tests which, amongst others, H. T. Kalmus has carried out for the Department of Mines of Canada, and a memoir published by that Department gives a more complete account of the properties of cobalt than any previous publication [11].

Cobalt metal resembles nickel in colour, but has a slightly blue cast. Its specific gravity is 8.8 to 8.9 and its hardness is 124 on the Brinell scale. The melting point is 1478°C . The tensile strength of pure cast and unannealed cobalt is about 34,400 lb. per sq. in. and is slightly higher when the metal has been annealed. Rolling adds to the tensile strength, which may reach 100,000 lb. to the sq. in. in a swaged wire. With a carbon content up to 0.3% the tensile strength of cobalt is practically doubled. When either pure, or with a small carbon content, cobalt is readily machined, and in the latter case it may be swaged down from cast bars to wires of any desired

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diameter. Pure cobalt wire has been found to have a specific electrical resistance of 89.64×10^{-7} ohms per centimetre cube at 18°C. , or about 5 times that of pure copper; but if annealed *in vacuo* the specific resistance is reduced about 5%. With less than 0.5% of impurity the specific resistance may be trebled.

Cobalt is magnetic at all temperatures up to about 1100°C. The mean specific heat of cobalt between 15° and 100°C. is 0.1053. The atomic weight is 59.0. The weight per cubic inch is 0.310 lb.

USES OF COBALT

The cobalt compounds used as pigments form a series of considerable value for their inherent properties, but their high cost prohibits their general use.

Smalt, bleu d'azur, or bleu de saxe, the manufacture of which in Saxony dates from the sixteenth century, is a blue glass, essentially a silicate of potash and cobalt. Smalt, as formerly prepared in Saxony, is obtained from smaltite with which bismuth is usually associated. The ore is heated sufficiently to liquefy out the bismuth; is crushed and is strongly roasted in a reverberatory furnace. The product is a crude cobalt oxide variously known as *zaffre*, or *zaffler*. This is mixed with potassium carbonate and white quartz, and fused in a glass-making furnace. A small quantity of arsenious oxide, obtained as a sublimate in roasting the ore, is added to the mixture as a purifying agent. It acts in combining with iron, copper or nickel in the ore to form a speiss, which settles at the bottom of the melting furnace, leaving a cobalt glass practically free from these impurities at the top. This top portion is ladled off with iron spoons and poured into cold water, giving a friable glass, which is afterwards ground to powder, levigated, dried and sifted. This method of producing smalt is, with little variation, employed at the present day in Saxony [12]. In recent years *zaffre*, or *zaffler* has been practically replaced in the ceramic trade by cobalt oxide.

Cobalt blue, Thénard's blue, cobalt ultramarine and *King's blue* are different names for artificially prepared cobalt aluminate; phosphoric acid and zinc oxide are sometimes added to

vary the tint. The pigment is usually obtained by heating together cobalt sulphate and alum, sometimes with the addition of zinc sulphate. Cobalt blue is said to be one of the most permanent blue pigments [13/p. 558].

Cerulean blue, or *bleu céleste*, obtained by heating together cobalt sulphate, tin oxide and precipitated silica or chalk, is a light blue pigment used as an artists' colour.

Cobalt green, *Rinman's green*, or *zinc green*, is formed by substituting zinc oxide for aluminium in cobalt aluminate (Thénard's blue). It has a bright green colour with a slightly yellow tinge.

Turquoise green, a bluish-green pigment, used chiefly for porcelain painting, is usually made by heating to redness a mixture of aluminium hydrate, chromium hydroxide and cobalt carbonate.

Indian yellow, *aureolin*, or *cobalt yellow*, is an artists' colour prepared by treating a solution of cobalt nitrate acidified with acetic acid, with a solution of potassium nitrite, the precipitate being washed, filtered, pressed and dried.

Cobalt brown is formed by calcining a mixture of ammonium sulphate, cobalt sulphate and ferrous sulphate.

Red and pink cobalt compounds are of little technical value. Cobalt arsenate strongly heated and ground yields a pinkish red powder. The precipitate from a solution of cobalt salt with sodium phosphate is pink, changing to violet when heated [6/p. 86].

Cobalt magnesia pink is obtained from precipitated magnesium carbonate mixed to a thin paste with cobalt nitrate solution, and then dried and heated.

Cobalt bronze is a phosphate of cobalt and ammonium, of a violet colour with a bronze-like metallic lustre [6/p. 85].

Although most of the cobalt colours referred to above have considerable permanence, their high cost and generally poor covering power, as compared with cheaper pigments of similar tints, prevent their extensive use, and their application as paints is practically limited to artists' colours.

In the enamel, glass and pottery industries, however, cobalt compounds are practically the only blue colouring matters employed, with the exception of the turquoise blue given by

oxide of copper, and these industries are the chief consumers of cobalt compounds. The silicate, aluminate, phosphate, arsenate, and also nitrate of cobalt are frequently used instead of the oxide, because they give better and more uniform colouring. Added alone to a glaze they give a beautiful deep blue of slightly violet tinge; with alumina, a sky-blue colour is produced, while the addition of zinc oxide gives an ultramarine tint. A small percentage of cobalt oxide or of a cobalt solution is sometimes added to the porcelain body to counteract the yellow colour due to the presence of iron, the effect being to whiten the ware [6/p. 84].

Organic compounds of cobalt, such as the resinate, oleate, linoleate, have been used as driers of oils, especially of soya bean, and possibly of other cheap oils used as substitutes for linseed oil in paint [14/p. 968]. The acetate has also been offered by chemical manufacturers as a paint drier [15].

Many of the soluble salts of cobalt are pink and deliquescent. If a weak solution of one of them, such as the nitrate or chloride, is used as the so-called "sympathetic" ink, the writing is practically invisible, but on heating the paper the combined water is driven off and the writing becomes blue and visible, gradually disappearing again on cooling and with absorption of atmospheric moisture [6/p. 86].

Cobalt nitrate is useful in the blow-pipe examination of minerals and by the different colours it produces with certain metallic compounds, such as those of aluminium, zinc and magnesia, often assists in their identification.

COBALT ALLOYS

The work undertaken by H. T. Kalmus for the Canadian Department of Mines included the investigation of certain cobalt alloys, one of which is the alloy with the formula, Fe_2Co . The value of this alloy is principally in its magnetic properties, which are such as should render it of great value in parts of electro-magnetic machinery where extreme magnetic densities are required. The employment of this alloy in the construction of electric machinery would permit of such

machinery being made much lighter, with, at the same time, a higher efficiency [16].

K. Honda and S. Saito have described an alloy, suitable as a permanent magnet in electrical instruments, containing the following percentages : Cobalt, 30 to 40 ; tungsten, 5 to 9 ; chromium, 1.5 to 3 ; and carbon, 0.4 to 0.8 [16A].

Similar magnet alloys have produced very strong and extraordinarily permanent magnets, particularly for use in magnetos for ignition purposes, by this means dividing their weight by 3 or even by 4, and making them more efficient as well as very much smaller. A plain carbon steel has usually a magnetic property of 200,000 (B-H) maximum.¹ Chromium steels, used in the United States, have from 240,000 to 250,000 ; while, with 35% cobalt, as much as 900,000 can be reached [16B].

As a steel alloying element, cobalt has been applied with notable success in the production of high-speed tool steels. Steels containing 4% of cobalt in addition to tungsten and chromium make tools which retain their edge well at or near a red heat and successfully cut or turn manganese and nickel-chromium steels. In the form of a cold saw such steels have been found to be less satisfactory, their more valuable property being their "red-hardness."

A German steel, somewhat misleadingly termed "iridium" steel, contains approximately in percentages Cobalt 4.25 ; tungsten 16.0 ; chromium 3.55 ; vanadium 0.67 ; molybdenum 0.80 ; and carbon 0.60.

Ferro-cobalt containing about 70% cobalt is the usual form in which the cobalt is added to steel, but it has recently been proposed to introduce the cobalt in the form of cobalt fluoride, which can be produced more cheaply.

Small percentages of cobalt added to pure iron gives alloys resistant to corrosion and suitable for roofing.

Alloys of cobalt and chromium, on account of their hardness and resistance to corrosion, are much used in "stainless" cutlery. The original "stellite" of E. Haynes is one of these alloys, containing 75% cobalt and 25% chromium.

¹ B is the magnetic flux density or induction and H the magnetising force or field intensity expressed in c.g.s. units.

THEIR OCCURRENCE, CHARACTERS AND USES 15

Table knives of this alloy could be used in vinegar and acid fruit juices without tarnishing or appreciable loss of lustre. Afterwards tungsten and molybdenum were added, making the stellite alloys exceedingly hard [4/p. 452]. In some experiments recorded by E. Haynes [4A/p. 249] on alloys with the chromium content maintained at 15% it was found that the alloy gradually increased in hardness with increasing percentages of tungsten. With 5% tungsten it becomes distinctly harder, and with 10% a tool can be made from it with a fine cutting edge, suitable both for cold chisels and wood working tools. With 15% tungsten the hardness increases. The alloy can still be forged but with increasing difficulty with the tungsten content up to 25%; beyond this point, forging is no longer possible. The alloy can, however, be cast into bars and shaped by grinding into lathe tools. Such tools are highly efficient, especially in the turning of steel, since they retain their hardness when run at high speeds. When the tungsten is increased to 40% the resulting alloy still retains its cutting qualities. Further additions of tungsten produce brittleness [6/p. 98]. Molybdenum produces somewhat the same effect as tungsten, only a smaller proportion is required. An alloy containing 10% molybdenum makes an excellent lathe tool. A typical analysis of a molybdenum stellite is given in the Imperial Institute monograph, *Molybdenum Ores* (p. 10).

A cobalt-chromium alloy known as "cochrome" may be swaged into wires which are in some respects superior to "nichrome" wires when used for electric heating elements. These wires are said to be less readily oxidized than nichrome at high temperatures, and possess a high melting point.

An alloy of 40% cobalt and 60% tin is extremely resistant to acids, even aqua regia, but is brittle. The addition of 5 to 20% of this alloy to molten copper gives, however, a product which can be machined and still retains a high degree of non-corrodibility [17].

The addition of 0.5% cobalt to a brass containing 80% copper and 20% zinc is said to increase the tensile strength by about 18% [13/p. 560].

Light alloys of aluminium and cobalt usually contain from

9 to 12% cobalt; are coarsely crystalline and are but little stronger than pure aluminium. The addition of tungsten to the extent of 0.8 to 1.2% to this alloy renders the grain very much finer and increases the tensile strength to two or three times that of pure aluminium [15]. Such alloys have a specific gravity between 2.8 and 2.9; they work and polish well and are not readily corroded by atmospheric agencies. Molybdenum, substituted for tungsten, appears to have a similar effect. An amalgam of cobalt with mercury is used in dentistry.

ELECTROPLATING WITH COBALT

The Canadian Department of Mines caused investigations to be carried out by H. T. Kalmus as to the suitability of cobalt for electroplating as compared with nickel [18]. Of many plating solutions tried, the best were found to be (1) cobalt-ammonium-sulphate, 200 grams dissolved in a litre of water, and (2) cobalt sulphate, 312 grams, sodium chloride, 19.6 grams, dissolved in a litre of water with boric acid sufficient to form a nearly saturated solution. Both of these were quite satisfactory and possessed a higher conductivity than standard commercial nickel plating solutions. This permits operating at a lower voltage for a given speed of plating.

At higher voltages, plating from the first solution is four times, and from the second solution fifteen times more rapid than with the fastest nickel plating solutions.

The cobalt deposit is adherent, hard and uniform, and may be buffed to a brilliant surface. It deposits well in all indentations and withstands the bending, hammering and burnishing tests ordinarily applied to nickel plate. The second solution, operating at 150 amperes per square foot, will deposit in one minute as satisfactory a plate as the best nickel bath operating at 10 amperes will deposit in one hour, the actual weight of the cobalt deposit being therefore approximately one-fourth that of the nickel.

This economy in metal counteracts the increased cost of cobalt as compared with nickel, and the rapidity of the process permits of a larger output of work, of smaller plating room and of the use of mechanical devices for passing the articles through

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the bath, all of these tending to economy. In spite of these advantages the plating of cobalt has not come generally into use.

Cobalt can be deposited on brass, steel, copper, tin, nickel-silver, lead and britannia metal [13/p. 560].

PRICES OF COBALT

The principal market for cobalt and its compounds has hitherto been in New York, and prices there have been subject to considerable variation in recent years, as shown by the following table :

	Price ¹ \$ per lb.	1914.	1915.	1916.	1917.	1918.	1919.	1920.	1921.
Metal .	highest	2.00 ²	1.70	1.50	2.00 ²	2.50	3.00	6.00	6.00
" .	lowest	1.25 ²	1.60	1.25	1.50 ²	2.25	2.50	3.00	3.00
Oxide .	highest	—	—	—	1.50	1.65	1.65	4.10	4.00
" .	lowest	—	—	—	1.00	1.50	1.50	2.00	2.00

¹ *Mineral Industry* (annual).

² *Min. Res. U.S. Pt. 1, U.S. Geol. Survey* (annual).

WORLD'S PRODUCTION OF COBALT

No reliable statistics of the world's production of cobalt are available. In one case only—that of Canada—is the production expressed in terms of the metal; in other cases production is expressed in terms of ore or mixed compounds which give little information as to the content. The Canadian production is probably about four-fifths that of the world. For recent years of metallic cobalt it was as follows :

	1914.	1915.	1916.	1917.	1918.	1919.	1920.	1921.	1922.
Short tons .	351 ¹	206 ¹	400 ¹	337 ¹	380 ¹	298 ¹	273 ²	98 ²	285 ²

¹ *Ontario Bur. Mines, Ann. Repts.*

² *Canada Dept. Mines, Ann. Rept., 1920.*

³ *Min. Prod. Canada, Dominion Bur. Statistics.*

The United States produces an appreciable quantity of cobalt as a by-product of the electrolytic refining of copper

obtained from ores mined in Missouri, from Canadian ores, and from copper imported from Europe, mainly from the Belgian Congo ; but no official records have been published since 1904, excepting for the year 1908, when the production of cobalt oxide amounted to 100,000 lb. [6/p. 17].

CHAPTER II

SOURCES OF SUPPLY OF COBALT ORES

(a) BRITISH EMPIRE

EUROPE

GREAT BRITAIN

COBALT ore deposits have been discovered in various parts of the British Isles, but none has proved to be of any importance. Small quantities of asbolite containing both nickel and cobalt were mined at Moel Hiraddug near Rhyl in Flintshire between 1873 and 1890. The total output for that period was 1,264 tons of mixed ore valued at £6,784.

The deposit was discovered in 1870 by testing with a blow-pipe the black matter forming stringers in limestone [19/p. 102]. The asbolite occurred as black and friable nodules, up to the size of a hen's egg, irregularly distributed in red clay, filling *swallows*, or large vugs in the Carboniferous limestone. The mineral was mixed with hæmatite and fragments of limestone. Cobalt formed 1%, and nickel from 0.4 to 11%, of the mass. One of the "swallows" was 262 ft. in depth, from 6.5 to 10 ft. in width, and 88 ft. in horizontal length [20] [21/p. 617].

The copper ores mined at Alderley Edge and Mottram St. Andrews in Cheshire for many years up to 1877 contained a very small proportion of cobalt. The stratified rocks in this locality have been upheaved, forming an escarpment and exposing the Lower Keuper sandstone and a conglomerate bed immediately below it. Both these are more or less mineralized, chiefly by impregnations of copper carbonate. In the sandstone, a band of about 40 to 50 ft. thick is mineralized; in the conglomerate, the cementing material only contains mineral. The copper ore obtained from this deposit was treated with

hydrochloric acid, which dissolved most of the copper and the cobalt. The copper was precipitated on iron, leaving the cobalt still in solution, from which it was precipitated by milk of lime [22/pp. 266-85].

Cobalt minerals in small quantities have been found from time to time in several of the metalliferous mines of Cornwall and Devon. According to Pryce [23] cobalt was found at Wheal Trugo, St. Columb, Cornwall, in a vein from 4 to 6 in. thick, at and near the junction with a copper lode; also at Dolcoath and several other Cornish mines. De la Beche states [24] that cobalt was found in a cross-course, adjoining a copper lode, at Wheal Sparnon, near Redruth. He also mentions other mines in Cornwall and Devon in which cobalt was found to occur. About 1,700 lb. of an inferior quality was sold from Wheal Huckworthy, Devon, in 1820. The cobalt ores found in these two counties were mostly smaltite and erythrite, but cobaltite and asbolite have also been noted. At the Herland mine, Gwinear, a cross-course at a depth of about 750 ft. contained, on either side of the point of intersection with the main lode, galena, native bismuth, cobaltite, argentite and native silver. At Wheal Ann, Phillack, native capillary silver occurred in smaltite and cobaltite; and, in the Willsworthy mine, at a depth of 60 ft. from surface, the lode from foot-wall to hanging-wall had the following section: smaltite and capillary native silver in a ferruginous gangue, 3 to 6 in. wide; white amethystine quartz (centre) chalcopyrite, 3 to 9 in. wide [25].

From 1854 to 1861, about 134 tons of cobalt and nickel ore were raised from St. Austell Consols, and, much more recently, about 13 tons of similar ore, from Fowey Consols and East Pool [26].

Erythrite occurs as a secondary mineral in the old Hilderstone mine of Linlithgowshire, Scotland. This and the old Coille-Chraghad mine of Inverary are referred to in the Imperial Institute monograph, *Nickel Ores* (p. 27). An analysis of the pentlandite from the latter mine gave about 1% cobalt [27/p. 135]. A small quantity of cobalt bloom (erythrite) was formerly found in McCallum's Level at the Tyndrum mine on the borders of Argyllshire and Perthshire [27/p. 96].

In 1759 a large mass of cobalt ore was encountered in the old Alva silver mines of Clackmannanshire, and a quantity was wrought, which was afterwards sold for pottery purposes. Two veins are said to have been worked, one trending N.W. and the other E.W. They were both from 3 to 6 ft. in thickness, and the filling consisted of barytes, calcite and quartz, carrying argentite, chalcopyrite and arsenopyrite, together with malachite, erythrite and native silver. A recent analysis of the cobalt ore gave the following percentages: Cobalt, 31·85; iron, 10·24; copper, 9·77; arsenic, 33·3; galena, 7·53. The underground workings are only a few fathoms in depth [27/p. 144].

Some cobalt ore occurs in the disseminated chromite deposit of Corrycharmaig, Perthshire, described in the Imperial Institute monograph, *Chromium Ore* (p. 16).

ASIA

INDIA

A mixture of cobaltite and danaite, locally known as *sehta*, has been found as minute crystals in dark-grey slate, containing chalcopyrite and pyrite, of the Aravalli Series at Khetri and other places in Rajputana. The minerals were determined by F. R. Mallet [28]. Two copper mines, Babai and Bagor, were formerly worked here, and the *sehta* raised therefrom was used mainly by the Jaipur jewellers for producing a cobalt-blue enamel. Not more than 200 lb. a month was produced at either of the mines, and the extraction was discontinued about 1908 [29]. The old mines have recently been examined by the Indian Geological Survey with a view to reopening them to supply the local demand for cobalt, but the result of the examination showed this to be inadvisable [30].

Indications of the presence of cobalt have been detected in the sulphide ores occurring near Arumanallar, Travancore, Madras. A surface sample yielded 0·08% cobalt. Small quantities of cobalt are frequently detected in the Indian manganese ores. A species of manganiferous iron ore from Olatura, Kalahandi State, Bihar and Orissa, assayed 0·82% cobalt

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oxide [29]. Asbolite, in nodules, associated with manganese and imbedded in white clay, has been reported at Houtzai, Tavoy, Burma. Linnæite has been recently identified among some copper ores sent from Sikkim [31]. Erythrite is sometimes found as an incrustation on the massive zinc-lead sulphide ores of the Bawdwin mines, Burma.

The chief demand for cobalt oxide at the present time in India is in the manufacture of the blue glass used in making bangles.

AFRICA

UNION OF SOUTH AFRICA

Cobalt ore deposits have been found in various localities in the Transvaal. So far as they have been explored, the most important seems to be one at Kruis River in the Middleburg district, from which it is said cobalt ore was mined and exported many years ago [32].

The ore, in the form of smaltite, is in a country rock resembling aplite, but which Mellor describes as originally a felspathic sandstone or quartzite, which has been altered and partially recrystallized by contact with a very extensive basic igneous intrusion, which immediately overlies it. The ore-bodies occur at or near the line of contact. In the best exposure the ore is contained in a fairly well-defined, but thin, vein, lying 2 ft. from the junction plane, and parallel to it and to the bedding planes of the quartzite. Minor veins occur parallel to this vein, and there are also impregnations of ore in the country rock. The ore carries an appreciable quantity of gold [33/pp. 36-8].

At Balmoral, on the farm Eenzaamheid, about fifty miles east of Pretoria, are several approximately parallel lodes in country rock, described by Mellor as being most probably a shale, which has been intensely indurated, and to some extent recrystallized by thermo-metamorphic action. This rock, as well as the quartzite of Kruis River, are regarded as belonging to the Pretoria Series. The greater part of the gangue is composed almost entirely of dark green hornblende or actinolite. Felspar, calcite and quartz (largely secondary) also occur.

The cobalt minerals are smaltite and erythrite, the former occurring in masses up to 22 in. in diameter closely intergrown with actinolite. Mineralized dykes, connected with a neighbouring large basic igneous mass and intruded into a series of highly-altered sedimentary rocks, may be regarded as the origin of the Balmoral cobalt ores [33/pp. 39-43].

In the Rooiberg district, about two miles S.E. of the main group of tin lodes, is another group characterized by having tourmaline and sometimes felspar as the vein-filling, and by carrying wolframite and scheelite, with very little cassiterite. On the farm Hartebeestfontein some cobaltite occurs associated with the tourmaline [34/p. 96].

On the farm Witfontein, in the Waterberg tinfields, a sample of the tin ore, taken 68 ft. from the surface, is stated to have shown 1.5% cobalt and 2.1 dwt. gold per ton [34/p. 88].

NORTH AMERICA

CANADA

Ontario.—The well-known silver-cobalt ore deposits of the Cobalt district are five miles west from the northern end of Lake Temiskaming, which forms the eastern boundary of Ontario. They were discovered during the building of the Temiskaming and Northern Ontario Railway in 1903, and production began in the following year with an output of 158 tons of dressed ore, valued at £28,028. In the next few years the output of silver rapidly increased to a maximum in 1911, since when it has steadily declined.

The total production of the Cobalt mines for the 17 years ended December 31, 1920, was: Silver, 314,446,504 oz.; and, in short tons, cobalt, 9,911; arsenic, 4,605; nickel, 4,647; copper, 285.

As the above figures indicate, the ores mined at Cobalt owe their value chiefly to the silver content, the cobalt, nickel and arsenic being comparatively insignificant by-products.

A typical high-grade ore is said to contain about 10% silver, 9% cobalt, 6% nickel, and 39% arsenic, the remainder being gangue and small amounts of antimony, iron, sulphur, tellurium, etc. [9/p. 127].

The geology of the Cobalt district and the chief characteristics of the veins are described in the Imperial Institute monograph, *Silver Ores* (pp. 44-45). Mineralogically, there are four types of veins: (1) Flat or shear joint veins; (2) fault veins; (3) inclined joint veins; and (4) vertical joint veins [35/p. 112]; (1) are essentially barren, or only rich locally when near (2), (3) and (4), all of which often carry high-grade ore. The majority of the cobalt-silver veins belong to type (4), for they occupy narrow, nearly vertical, fissures or joints in the Nipissing dolerite (1,000 ft. thick), the Cobalt Series (600 or 700 ft. thick) and the Keewatin series. The Cobalt Series, which has yielded 80% of the silver won to date [36], consists of conglomerate, graywacke and quartzite, and is believed by W. L. Whitehead to be of fluvial origin [35/p. 105].

According to Campbell and Knight [37/p. 776] the order of succession of the minerals in the veins was as follows: smaltite, niccolite; then, after a period of movement and fracturing, calcite, argentite, native silver and native bismuth. E. S. Bastin [38/p. 228] considers that the arsenide minerals, together with breithauptite and ferruginous calcite, were deposited more or less contemporaneously, and were afterwards replaced by native silver, and to a minor degree by polybasite (?). Whitman [39/p. 146] regards the rough sequence to be calcite, cobalt and nickel arsenides and silver. It is generally conceded that the silver-cobalt veins in North Ontario were not deposited at very high temperatures. Whitman [39/p. 137] believes that the cobalt-nickel-silver ores of the Cobalt district were derived by diffusion and metasomatic fixation from the sill of Nipissing dolerite with which they are associated.

Some of the veins have been worked to a depth of 200 ft. or more in the Cobalt Series, but most of them are productive to lesser depths [9/p. 125]. The walls of the veins are sometimes impregnated with silver-cobalt ores for an appreciable thickness, often reaching a stopping width of 5 or 6 ft., rarely 15 ft., and in one instance 86 ft.

In 1920 and 1921 the Canadian Geological Survey undertook a resurvey of the Cobalt region, which was carried out by Cyril W. Knight and others. An article by Knight [36] contains a brief summary of the report which will appear

later. This article forms a very valuable supplement to the fourth edition of Miller's Report [9].

Perhaps the most significant fact which the resurvey has confirmed is the general limitation of silver to a zone at the base of the Cobalt Series, where it rests on the Keewatin, and a little below. This zone seldom extends to more than 150 to 200 ft. above, or more than 25 ft. below, the contact. Two notable exceptions to this are the Temiskaming and Beaver mines, where the Keewatin contains the richest ore. These mines are working the upper contact, and their joint production has been about 11,000,000 oz. of silver. In these cases the productive zone is about 125 ft. in depth, but the veins are 600 ft. above the contact, and have been proved to extend downwards into the sill for at least 250 ft. At the O'Brien mine, the lower contact of the sill with the Keewatin furnishes the payable ore, and the vertical limit is about 100 ft. In this mine the richer ore is found in the sill and not in the Keewatin. One of the most important structures regarding the ore-bodies is the general occurrence of the silver-cobalt ore-shoots at and near contacts. For instance, in the Violet mine, there are no veins on the surface, but a shaft was sunk 330 ft. in the dolerite sill, and about 250,000 oz. silver have been obtained up to 1922 along the lower contact between the sill and the Keewatin.

No economic quantities of silver have been found at a greater depth than about 800 ft. below the surface. It appears from this that the present surface may have some bearing on the depths to which profitable bodies of silver may extend.

In some instances faults appear to have acted as barriers to the silver solutions, although calcite veins carrying cobalt and nickel arsenides may and do occur beyond them. In other instances faults appear to have dammed back the silver solutions, but only locally.

More attention is now being paid to geological structure, and diamond drilling precedes mining.

Cobalt is reduced from these ores, chiefly in the form of cobalt oxide and cobaltic material containing nickel and a little silver, in smelters at Deloro, Thorold and Orillia in Ontario; but metallic cobalt in increasing quantity is also being produced at these works. Other smaller plants are irregularly

operated at North Bay, Kingston and Welland, and a considerable amount of graded ore is sent to the United States for treatment. The extraction of the nickel and cobalt and their separation is a complicated chemical process, which is more fully referred to in another section (*see p. 9*). The calcined product is the oxide (Co_3O_4), a black compound in the form of a powder, which can be reduced to metallic cobalt by carbon and some other reducing agents in a reducing furnace.

As to the future of mining at Cobalt, it is the opinion of Knight, that although the most productive period has passed, Cobalt or the outlying areas will be producing silver, and therefore cobalt, for generations to come.

The more productive areas have been thoroughly explored by various kinds of underground workings, and it is unlikely that further important vein systems will be found. One important exception may be made in the case of the Nipissing mine, which includes 846 acres in the heart of Cobalt, only a portion of which has been explored. There are a few other central properties, which merit further development, and the drift-covered areas north of the Violet mine are attractive from a speculative point of view. The south end of Cobalt itself, known as South-East Coleman, is considered to be worth attention, and the upper contact of the sill and Keewatin will no doubt be further explored on account of the favourable results obtained at the Beaver and Temiskaming mines.

There are silver-cobalt mines at various places outside the immediate neighbourhood of Cobalt, and from a few of these considerable production has been recorded.

Generally, the geological conditions resemble those of Cobalt, and the ores are associated with a dolerite intrusion, but whether the dolerite sill found at these places is part of that found at Cobalt or is a separate intrusion is not quite certain. But they are, at any rate, considered to be of the same age.

One of the outlying productive areas is in South Lorrain township, sixteen miles south of Cobalt. This area had yielded, up to the end of 1921, 3,298,006 oz. silver, to which the Wettlaufer mine had contributed largely. This mine is no longer an important one. Three parallel veins occur in the

Nipissing dolerite. Of these, the two northerly ones had rich shoots showing native silver in sheet form, while the south vein carried smaltite with low silver content. Other veins, similar to the latter as regards country rock and filling, occur in the region. The Keeley mine, formerly one of the big producers, has shipped very little ore in recent years. The formation is Keewatin, and native silver occurs in wire form, flake-like sheets and hair-like tufts, associated with smaltite in a gangue of quartz and calcite. At a depth of 130 ft., more or less, cobaltite was associated with the silver ore. A sample of massive ore from a vein near the west side line of the property showed it to be smaltite-chloanthite containing the following percentages: Cobalt, 10; nickel, 8.16; arsenic, 68.72; sulphur, 0.42; and silver, 8.7 oz. per ton. On the Jowsey Woods mine, leaf silver in small flakes has been found in one vein, associated with smaltite, chloanthite and native bismuth. Minute crystals of chloanthite are scattered through the gangue. On another claim, smaltite and niccolite occur together. A sample of the massive ore gave the following percentages: Cobalt, 15.92; nickel, 11.18; arsenic, 60.38; silver, a trace. About 15 tons of smaltite were obtained from this claim at a depth of 100 ft. On the Frontier mine, a vein occurring in the conglomerate (Cobalt Series) carries smaltite and chalcopyrite in calcite and quartz, and silver a few feet below the surface. Smaltite and niccolite have been found on a number of claims in well-defined veins [9/pp. 143-4].

The Gowganda district is described in the Imperial Institute monograph, *Silver Ores* (pp. 45-6). The district, which lies about 50 miles N.E. of Cobalt, produced 6,135,012 oz. silver up to the end of 1921. At Gowganda, strong veins of smaltite and niccolite have been found in the Keewatin, as well as in the conglomerate (Cobalt Series). The vein-filling is usually calcite with native silver, smaltite, niccolite and, occasionally, native bismuth and bismuthinite. In some of the smaller veins the fissures have been entirely filled over short distances with smaltite, niccolite and silver [9/pp. 179-80].

The township of Casey, lying 13 miles north of Cobalt, produced 2,941,512 oz. silver to the end of 1921. The principal

mine is the Casey Cobalt, where the veins have a filling of smaltite, chloanthite and niccolite in a calcite gangue [9/p. 145].

Native silver was not found at surface, but it occurred at no great distance below, and a large amount of silver has been raised from this mine.

South of Lake Wendigo there have been several discoveries of veins in dolerite and gabbro carrying cobalt bloom in a quartz gangue, as well as massive smaltite, but work on these has not yet passed beyond the prospecting stage [9/pp. 149-51].

West of Bay Lake on the Montreal River in banded slates and quartzites cut by dolerite and gabbro dykes are veins carrying erythrite, chalcopyrite and pyrite in a calcite gangue. Deeper down in the veins, small quantities of smaltite are found, and sometimes niccolite [9/p. 154].

The Shining Tree silver area is about 15 miles S.W. of Gowganda Lake. Several prospects have been opened on veins carrying native silver, cobalt, copper and other minerals. These veins are found in dolerite chiefly, but some are in conglomerate. The vein filling is either calcite or quartz.

At Otter, near Thessalon, on the north shore of Lake Huron, cobaltite and native bismuth occur in quartz veins in dolerite [9/p. 196].

The Lake Superior deposits adjacent to Port Arthur contain nickel, cobalt and arsenic, but in smaller amounts than those of Cobalt. Here also the veins occupy vertical fissures in slightly inclined pre-Cambrian rocks, but the ore is found in bunches or pockets, and is not distributed through the vein. The gangue minerals are quartz, barytes, calcite and fluorspar, in which occur blende, galena, pyrite, chalcopyrite, native silver and argentite.

The nickel area of Lake Shebandowan, in the district of Thunder Bay, about 73 miles west of Port Arthur, is described in the Imperial Institute monograph on *Nickel Ores* (p. 37). Analyses of 11 samples from a lode, varying from 18 to 34 in. in width, gave the following range of percentages: Nickel, 0.62 to 5.44; copper, 0.67 to 3.43; cobalt, 0.17 to 0.38. The nickel ore is polydymite. Niccolite also occurs, and the rare arsenides skutterudite (CoAs_3) and gersdorffite (NiAsS) have been identified in these deposits [7/p. 231].

At Silver Islet, niccolite, cobalt bloom and macfarlanite¹ also occur [9/p. 201].

Cobalt is present in small amount in the nickel-copper deposits of Sudbury, and a small recovery was reported from 1892 to 1894.

With a view to encouraging the production of refined nickel and cobalt compounds within the province, the Ontario Government passed a Metal Refining Bounty Act under which a bounty of 6 cents per pound was payable for all refined nickel and cobalt compounds refined in Ontario. This Act ran for five years to April 20, 1912, and at the end of that period was extended for a further five years, since when the bounty has been discontinued.

The quantities of the various cobalt products upon which the bounty had been paid up to April 20, 1917, the end of the second period, are given in metric tons as follows [8/p. 481]:

Oxide, 1,227; metal, 206; sulphate, 38; carbonate, 2.7; hydroxide, 2.6; stellite, 53.

Manitoba.—A discovery of cobalt minerals at the contact of granite and greenstone has been made east of the Big Island Lake district of Manitoba. These minerals are smaltite and erythrite associated with chalcopyrite, but although they appear to be fairly widely distributed in the district the value of the deposits has not yet been determined.

The ores of Cobalt, Ontario, owe their value chiefly to their silver contents, but it remains to be proved whether this occurrence in Manitoba possesses a similar association of silver with cobalt [40].

Tables of Canadian production and exports of cobalt materials are as follow:

Production of Cobalt Materials in Canada

(Hundreds of pounds)

	1918. ¹	1919. ¹	1920. ¹	1921. ²	1922. ²
Cobalt metal and metal contained in oxide, etc.	7,371	5,303	5,460	1,961	5,700

¹ *Ann. Repts. Min. Prod. Canada, Mines Branch.*

² *Min. Prod. Canada, Dominion Bureau of Statistics.*

¹ A rare mineral containing 78% silver with arsenic, cobalt and nickel.

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*Analysis of Exports of Cobalt Materials from Canada*¹ (Hundreds of pounds)

Years ending March 31.	1918.	1919.	1920.	1921.	1922.
METALLIC COBALT:					
United Kingdom . . .	675	433	1,765	225	—
France	—	266	—	—	—
United States	2,282	2,178	827	1,188	328
Other Countries . . .	—	—	11	11	266
Totals	2,957	2,877	2,603	1,424	594
COBALT ALLOYS:					
United Kingdom . . .	332	388	49	99	58
France	147	169	1	—	4
Italy	176	—	—	—	—
United States	8	13	2	11	—
Other Countries . . .	14	—	2	—	9
Totals	677	570	54	110	71
COBALT COMPOUNDS:					
United Kingdom . . .	1,856	1,729	1,632	1,716	112
France	112	—	224	112	455
United States	3,142	3,071	2,015	1,401	1,647
China	—	60	119	20	71
Japan	96	1,540	1,087	877	217
Other Countries . . .	—	2	—	32	522
Totals	5,206	6,403	5,077	4,158	3,024

¹ Monthly Repts., Trade of Canada. Dominion Bureau of Statistics.

*Imports into, and Exports from, Canada of Cobalt*¹

Calendar years.	1921.		1922.	
	lb.	\$	lb.	\$
IMPORTS:				
Cobalt ore	100	131	200	233
Products containing cobalt	4,382,275	346,070	7,343,477	443,869
Totals	4,382,375	346,201	7,343,677	444,102
EXPORTS:				
Cobalt alloys	8,617	46,591	4,022	21,398
Cobalt metallica . . .	59,435	141,199	111,830	288,776
Cobalt oxides and salts	190,483	405,300	430,024	770,511
Totals	288,535	593,090	545,876	1,080,685

¹ Prel. Rept. Min. Prod. Canada, 1922, Dominion Bur. Statistics.

AUSTRALASIA

AUSTRALIA

New South Wales.—Occurrences of cobalt ore are somewhat numerous in New South Wales, but only at the three places, Carcoar, Port Macquarie and Bungonia has ore been produced in commercial quantities, and then not in large amounts. The Carcoar deposit is on the top of a hill about three-quarters of a mile S.E. from Carcoar railway station. The geological formation here consists of a large mass of diorite, which is intrusive into chlorite and clay-slates. Both diorite and slates have been intersected by dykes of whitish-grey felsite ranging from a few feet up to 18 ft. in width. Parallel to one of the largest of these dykes, but at some distance away, partly in chloritic slate, and partly in a narrow diorite dyke thrown out from the main body, is a mineralized vein consisting of a succession of lens-shaped masses of ore containing glaucodot, molybdenite and nickel minerals, and their oxidation products. The following analyses give the main constituents of two samples taken from separate lenses [41/pp. 226-8]:

	No. 1.	No. 2.
	%	%
Arsenic	51.81	29.01
Cobalt	10.45	13.83
Nickel	0.59	0.39
Iron	11.86	15.78
Gangue	22.08	26.31

The deposit of Port Macquarie consists mainly of asbolite. The geological conditions suggest that sedimentary rocks have been intruded by basic igneous rocks, which have since been altered to serpentine. The sediments have become more or less metamorphosed, and now consist of an altered fine-grained sandstone. The upper part of the serpentine has weathered into a ferruginous earth in which the ore-bodies are chiefly found as irregularly-occurring nests and pockets of wad, in some instances associated with loosely-cemented chromite grains of no value. The following table of analyses

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gives the compositions of (1) an average ore and of (2) a picked sample [41/pp. 229-33]:

	No. 1. %	No. 2. %
Silica	8.06	6.40
Alumina	18.95	9.97
Ferric oxide	14.78	16.85
Manganese dioxide	31.05	36.50
Cobalt oxide	7.48	7.03
Nickel oxide	1.36	2.39
Chromic oxide	0.41	0.40
Lime magnesia, etc.	0.16	2.51
Water	17.19	17.62
	<hr/> 99.44	<hr/> 99.67

The Bungonia deposits are in several localities in the district of the same name. They appear to be of lacustrine origin and of Tertiary age, and rest unconformably upon Devonian claystone and quartzites. One of these, about three miles from Bungonia, has yielded ore, but it proved unprofitable. The ore fills the interstices of a coarse quartz grit, and is considered to have been deposited from percolating solutions. It is similar in character to that found at Port Macquarie, being a cobaltiferous wad. Concretionary nodules of this material are not uncommon, and constitute the richest portions of the deposit. A sample of average ore yielded on analysis 1.53% cobalt and 20.86% manganese dioxide [41/p. 233].

Exports of graded cobalt ore from New South Wales in long tons have been as follow:

1901.	1902.	1903.	1904.	1910.
111	34	153	55	10

In 1904, regular production ceased as the erratic nature of the ore-bodies then exposed did not permit of profitable operation [42].

Queensland.—About 19 miles south of Selwyn, which is 71 miles from Cloncurry, in Queensland, cobalt ore was discovered in 1919 at the contact of diorite with schists of supposed Silurian age. These schists form noticeable outcrops, and associated with them at a distance of a few chains from the diorite, are several prominent and apparently barren quartz

outcrops conforming to the strike of the country. The lode is from 1 to 3 ft. in width; it dips 74° to 80° , and lies parallel with the foliation of the schists on the hanging-wall, its strike being N. 5° W. Four shafts have been sunk at different points in this lode, samples of ore from these shafts assaying up to 20% cobalt. The ore minerals are cobaltite and erythrite. A picked sample of cobaltite recently assayed for the Department of Mines had the following percentage composition: Arsenic, 40.2; sulphur, 15.8; cobalt, 33.1; iron, 2.1; silica, etc., 8.3.

There is a quartz vein outcropping from the adjacent dyke of diorite at right angles to the cobalt lode, which contains cobaltiferous wad and brown iron ore. Although the vein is quite distinct from the cobalt lode at the surface, it is possibly related to it genetically, and it has been suggested that it might have been a channel of supply to the contact cobalt lode. An average sample of this wad contained 5.2% cobalt [43].

The output of sorted ore in 1921 was 85 tons, valued at £21,332 [44].

The present (1923) output of sorted ore is 50 tons per month, and a depth of 200 ft. has been reached.

South Australia.—Cobalt ores containing smaltite and other cobalt minerals have been found at Bimbowrie, near Olary on the Broken Hill Railway, but not in commercial quantity.

CHAPTER III

SOURCES OF SUPPLY OF COBALT ORES (*continued*)

(b) FOREIGN COUNTRIES

EUROPE

CZECHOSLOVAKIA

At Joachimsthal, in Bohemia, formerly part of Austria, are cobalt ore deposits which have yielded ore for over 400 years, and a small amount of ore is probably being mined at the present time. No recent information, however, is available, but for the five years ending 1901, the annual production of nickel and cobalt compounds in Austria averaged 37 metric tons and was doubtless from the Joachimsthal deposits.

The ore is found in E.-W. and N.-S. veins cutting beds of mica-schist, calc-schist and limestone, which are themselves cut by dykes of basalt. The veins are narrow, and the mineralization is complex, including native silver, argentite, polybasite, stephanite, tetrahedrite, proustite, pyrrargyrite, sternbergite, argento-pyrite, rittingerite, acanthite and cerargyrite as silver minerals; niccolite, chloanthite and millerite as nickel minerals; smaltite, bismuth-cobalt-pyrite and asbolite as cobalt minerals; and native bismuth, bismuthinite and bismuth ochre as minerals of bismuth. Besides arsenic ores (native arsenic and arsenopyrite), uranium minerals are also present, and other minerals occasionally found in small amounts are galena, blende, pyrite, marcasite, chalcopyrite and bornite. The gangue minerals are quartz, hornstone, calcite and dolomite [9/p. 213] [45/p. 285].

The ores first mined were rich in silver. After 1545 mining declined, but acquired new vigour when cobalt and bismuth became of value. From that time production has been carried

on with varying fortune, and since the discovery of radium the mining of the uranium ores has become a prominent feature of the Joachimsthal mining industry [46/p. 713].

At Dobsina, formerly in Hungary, Palæozoic slates are intruded by a sheet of diorite, which follows the contact with a stock of garnetiferous serpentine. Cobalt-bearing veins cut the diorite close to its contact with underlying chloritic schists which have been formed by alteration of the serpentine. Three lodes, being veins with a steep southerly dip, are easily recognized, as they divide into fan-like stringers above, and tend to disappear or become barren at a depth of 590 to 655 ft. The vein-filling consists of siderite, calcite, ankerite and some quartz, in which tourmaline needles sometimes occur. The ore minerals are irregularly scattered through the veins in pockets, parallel layers, and large compact bodies, and consist of smaltite and diarsenide of nickel. Chalcopyrite, bornite, arsenopyrite, löllingite (FeAs_2) and niccolite are occasionally present. The veins broaden upwards into trumpet-shaped expansions of coarsely crystalline siderite as much as 100 ft. thick, containing scattered nests of copper, nickel and other ores, and are worked as an iron ore deposit.

The cobalt-nickel ore production from 1840 to 1880 was 26,000 tons, but these deposits have not been worked for cobalt for many years [45/pp. 340-1].

FRANCE

The narrow silver-cobalt-nickel veins occurring in crystalline schist at Chalanches, Dauphiné, France, have already been referred to in the Imperial Institute monograph, *Nickel Ores* (p. 47).

Quartzose veins containing smaltite were prospected in 1784 at Juzet near Montauban-de-Luchon, Haute-Garonne. Some production of ore took place from this deposit, but details are lacking [6/p. 12].

In Alsace at the Sainte-Marie-aux-Mines veins of calcite, carrying smaltite, chloanthite and native silver, were once worked [6/p. 8].

GERMANY

There are two kinds of cobaltiferous lodes at Schneeberg, in Saxony, silver-cobalt or barytes-cobalt lodes, and bismuth-cobalt or quartz-cobalt lodes. They both belong to a system younger than the tin-copper and sulphide zinc-lead ores of the district. The silver-cobalt lodes, which were remarkable for their great richness in silver, occur in contact-metamorphic schists of Cambrian age at Schneeberg and Schlemma, as well as at Bockau and Aue, and carry silver minerals with subordinate cobalt, nickel and bismuth in a barytic gangue.

The most important lodes of the Schneeberg district, however, are those belonging to the bismuth-cobalt group, some of which are still being mined. The area is nearly 4 square miles in extent with Neustädcl in the centre. The numerous lodes in metamorphosed Cambrian schist were compared by H. Müller to a gigantic stock-work. They strike W.N.W. or N.N.W., and therefore meet at acute angles, and are from $1\frac{1}{2}$ to $3\frac{1}{2}$ ft. wide. Some are known for a length of nearly 2 miles and to a depth of about 1,000 ft. The filling consists of smaltite, earthy-cobalt, bismuth-linnæite, erythrite, niccolite, chloanthite, native bismuth (common), bismuth ochre, a little silver ore, arsenopyrite, pitchblende and other uranium ores. The gangue consists of quartz, hornstone, dolomite and calcite. As a rule the veins are barren or poor when they penetrate the underlying granite, but in the Weissen-Hirsch mine, rich uranium and cobalt ores were found in that rock. In this district, flat attrition zones with carbonaceous alum-shale material appear to have a favourable effect on the lodes [46/pp. 680-1]. These zones may be compared to the *Schwebende* of Annaberg and to the "black seams" of Marienberg described below. In the bismuth-cobalt veins are many pseudomorphs of quartz and hornstone, and rarely of chalcedony, after calcite, and sometimes after barytes. It is evident that the carbonates, especially siderite and calcite, were formerly far more abundant, and probably in association with barytes, but they were in part subsequently removed and replaced by silica [45/p. 344].

The discovery of these deposits dates back to the fifteenth

century, in the latter part of which they were worked for silver, but it was considerably later that cobalt came into use for colouring glass. From that date the colour industry rapidly developed in Saxony, and colour works, treating the Schneeberg ores, were also erected in Holland.

It has been estimated that the total production of pigment by the end of the eighteenth century was from 5,000 to 6,000 tons per annum, representing 300 or 400 tons of cobalt, which is probably not far below the world's total consumption of cobalt for all purposes at the present time. Of late years, however, many other pigments of a less costly nature than smalt have been discovered and are used as substitutes.

At Annaberg, in Saxony, veins of cobalt ore closely resembling in composition those of Schneeberg and of Joachimsthal (Czechoslovakia) occur in grey gneiss, which is traversed by dykes of porphyritic micro-granite, lamprophyre, and basalt. The silver-cobalt veins are found sometimes cutting these dykes, but in other cases following them for long distances. A feature of the mining industry of Annaberg is the presence of sheets of decomposed rock in the gneiss up to $6\frac{1}{2}$ ft. in thickness, dipping at about 20° and known as *Schwebende*. These sheets are usually dark in colour from the presence of fine earthy carbonaceous substances, interspersed sometimes, but not always, with pyrite or chalcopyrite. The silver-cobalt veins, which usually dip steeply, cross these sheets, and at the points of intersection frequently show extensive enrichment, indicating that these sheets have materially influenced the deposition of ore [45/pp. 287-91].

The chief ore minerals are pyrargyrite, proustite, argentite, native silver, cerargyrite, smaltite, chloanthite, gersdorffite, annabergite, native bismuth and busmuthinite.

The vein-filling consists mainly of barytes, fluorspar, quartz and siderite. In some cases rock fragments and attrition-clays fill the veins, and argentiferous vein-clays have sometimes been mined.

i Mining in the Annaberg district dates back to the first half of the fifteenth century, when, it is said, a mine was opened for copper. Near the end of that century and the beginning of the next numerous silver veins were discovered and worked.

and it has been estimated that from 1496 to 1600 ore to the value of 24,300,000 marks had been mined [45/pp. 290-1].

From 1560 to the middle of the seventeenth century, the industry declined, but revived when cobalt began to be utilized. From 1701 to 1850 it has been estimated that 1,311 metric tons of cobalt and 26,945 kg. of silver were produced. Since 1850 the mineral production of the Annaberg district has been of little importance.

At Marienberg, to the N.E. of Buchholz-Annaberg, lodes belonging to the silver-cobalt and sulphide zinc-lead groups occur, as well as tin lodes. Geologically the district is the same as that of Annaberg. There are two lode systems striking N.E. and N.W. respectively. The minerals present are galena, blende, pyrite, silver-cobalt minerals and pitchblende, the gangue being quartz, barytes, fluorspar and dolomite. Enrichment in silver occurred at lode junctions and at intersections with the so-called "black seams" (*Schwebende* of Annaberg). This district is to-day of no importance [46/p. 679].

A similar association of ores is found in several other localities in the Erzgebirge as well as at Wittichenau, and at Wolfbach in the Black Forest, where the veins occur in granite [45/p. 292]. In Thuringia, fault fissures in the *Kupferschiefer* and *Zechstein* are filled with barytes, calcite and fragments of country rock, together with smaltite, asbolite and erythrite. These deposits have been worked at Schweina near Libenstein [45/p. 341].

The palæopicrite of Dillenburg, Nassau, contains cobalt associated with nickel, copper and bismuth [1/p. 426].

Cobalt minerals occur at Querbach and Giehren in the Riesengebirge, where mica-schist near its contact with gneiss is impregnated with cobaltite, chalcopyrite, pyrite, pyrrhotite, arsenopyrite, blende, galena, magnetite and cassiterite.

In the Fichtelgebirge, ores of cobalt and nickel are associated with siderite, bismuth and barytes, while siderite and copper ores are their associates in the Siegen district of Prussia.

According to *Mineral Industry* (1921) there was an average annual production in Prussia between 1904 and 1911 of 107 metric tons of cobalt ore and products.

A deposit of silver ore containing nickel and cobalt has been

worked in past years at Andreasberg in the Harz Mountains. The largest of the veins do not exceed 20 in. in width, and are fissures in Silurian clay-slates and quartzites; they appear not far from the intrusive mass of the "Brocken" granite. The mineralization of the veins is not unlike that of the Schneeberg and Annaberg veins, the nickel and cobalt minerals being chiefly niccolite and smaltite respectively. The silver minerals, which were deposited later, include pyrrargyrite and proustite, and native silver is common.

The mines on this deposit reached a depth of 2,700 ft., but have been closed down for some years [47].

ITALY

Cobalt and nickel ore deposits occur at Varallo, Piedmont, Italy. These, although not extensive, are of interest, since in mineralogical composition and in their association with basic rocks they resemble those of Ontario and Norway. Like many other small deposits, they were worked in the period preceding the discovery of the New Caledonian ores, but were closed down after this, and have not since been worked. In 1876 two mines made a total production of about 2,800 tons of ore containing in percentages: Nickel, 1.20 to 1.44; cobalt, 0.36 to 1.00; copper, 0.50 to 0.72; and sulphur, 28 [48]. The geology of the region is described in the Imperial Institute monograph, *Nickel Ores* (p. 51).

NORWAY

Cobalt ore deposits occur at Modum in Southern Norway. The formation consists of thick quartzites with numerous very large and, principally, bedded intrusions of amphibolites and hornblende-schists (probably altered gabbros), as well as masses of true gabbro. There is a cobalt fahlband zone running N.-S. with an amphibolite (or, according to A. J. Phillips, diorite) intrusion, and dipping E. 80°. The Modum cobalt fahlband, in the Modum parish, in which the Skutterud mine (550 ft. deep) is situated, extends, with many breaks, through the long-abandoned Snarum mines for a length of 6 miles with a width of 250 to 300 ft. Within the fahlband zone are

micaceous quartzites, mica-schists, intrusions of thin amphibolite seams, as well as augen-gneiss. The principal cobalt mineral is cobaltite, associated with skutterudite (CoAs_3) and danaite (cobaltiferous arsenopyrite). There is some secondary erythrite. A little pyrite, pyrrhotite, chalcopyrite, arsenopyrite and molybdenite also occur. With the cobalt minerals the diopside mineral, salite, occurs frequently, together with some anthophyllite, tremolite and epidote. The cobalt minerals form impregnations chiefly within certain quartzite layers rich in mica and tourmaline. Each cobalt fahlband may be from 16 to 26 ft. in width, and there may be several of these close together, but separated from one another by barren rock and almost clean quartzite [46/pp. 1138-9].

According to C. Le Neve Foster [19/p. 26] there may be alternate bands of mica-schist and quartz-schist (quartzite), the cobalt minerals being, as already pointed out, mainly confined to the latter, as well as to bands of the mixed rocks.

The most successful period of working the Modum mines was from 1838 to 1839, when the output of cobalt concentrate amounted to 160 tons [45/p. 469]. During the period 1856 to 1898, cobalt products containing 257 tons of metallic cobalt were produced. The Skutterud mine was abandoned in 1898 [46/L, p. 1140].

SPAIN

Several mines in the valley of Gistain, in the Province of Huesca, Spain, near the French frontier, were worked for cobalt in the eighteenth century, and were reopened for a time in 1872. The chief cobalt mineral is a ferriferous smaltite associated with niccolite, native bismuth and busmuthite in a calcite gangue. The veins occur at the contact of schists with Palæozoic limestones.

At Guadalcanal, in Andalusia, veins containing ores of silver, cobalt and, occasionally, copper in a calcite gangue were at one time of importance.

No production of cobalt in Spain has been reported since 1897 [6/p. 21].

SWEDEN

Cobaltiferous deposits are known in Sweden at Gladhammer, near Westervik, in Kalmar Län; at Vena, north of Vettern; at Los, in Helsingland; at Tunaberg, near Njckjöping, in Södermannland; and at Hakanbol, in Örebro Län.

The first two are typical fahlband deposits. At Gladhammer they occur in mica- and quartzite-schists. The deposits are irregular and consist of cobaltite, pyrite and chalcopyrite, accompanied by linnæite and gersdorffite. At Vena the fahlbands are found in fine-grained micaceous gneiss. The cobaltiferous fahlbands of Sweden are of lower grade than, although otherwise resembling, those of Norway.

At Los the cobalt ores occur in the schistose portion of a foliated amphibolite or gabbro massif, which is enclosed in mica-schists and quartz beds. The gabbro is scattered with grains or contains enclosures of bornite, chalcopyrite, pyrite, blende, cobaltite, smaltite, linnæite, gersdorffite, quartz, calcite and anorthite.

At Tunaberg the cobaltite occurs in a bed of granular limestone in grey gneiss, and is accompanied by smaltite, chalcopyrite, chalcocite, some lead and silver, and the contact minerals hornblende, mica and serpentine. The mine reached a depth of nearly 600 ft.

At Håkanbol cobaltite and glaucodot are found in slate and limestone.

Bismuth occurs to a small extent in some of the Swedish deposits.

Several of the deposits were formerly worked for copper as well as cobalt, but all have lain idle for years [22/p. 535] [45/p. 469] [46/p. 1140].

ASIA

NEW CALEDONIA

Before the discovery of the Cobalt ore deposits of Ontario in 1903, it was estimated that New Caledonia was supplying 85 to 90% of the world's requirements of cobalt. Canadian competition, combined with lack of freightage and other difficulties due to war conditions, appear to have crippled the

cobalt mining industry in the island. It is believed, however, that large reserves of cobalt ore remain, and possibly mining will be resumed when conditions become more favourable.

The geology of the nickel-cobalt zone of New Caledonia is described in the Imperial Institute monograph, *Nickel Ores* (p. 61).

Nickel and cobalt minerals occur in the decomposition products of serpentinized peridotites. The cobalt is found in the form of asbolite. The ultimate result of the weathering of the serpentine is a ferruginous earth known as "red earth" consisting to a large extent of ferric oxide, and it is in this material that the asbolite occurs in the form of nodules. In one deposit, the decomposed material occupies a basin-like depression in the serpentine, and reaches at the centre a depth of 170 ft. and at the margin, a depth of 33 ft. ; but, generally, the New Caledonian ore-bodies are much shallower. Ore deposits of this kind are obviously too irregular in character to admit of any close estimation, but there is without doubt in New Caledonia a considerable reserve of this class of ore. Vogt considers that the nickel and cobalt ore-bodies have been derived from the serpentine by lateral secretion, and states that this is one of the few instances in which the lateral secretion theory can be satisfactorily applied. Nickel and cobalt are particularly associated with peridotite rocks, and the first step towards the formation of an ore-body is considered by Vogt to be a magmatic differentiation of the nickel and cobalt minerals from the parent rock, not to the extent of forming a commercial ore-body, but of producing some concentration of these minerals. Weathering agencies subsequently produced soluble compounds of nickel and cobalt with their associated minerals. These soluble compounds were dissolved by surface waters, which filled the fractures in the serpentine and there deposited their dissolved contents, forming mineralized veins. The weathering of the serpentine has resulted in the breaking up of these formations, and in the production of the detrital material in which the asbolite nodules are now found [46/pp. 191 and 953].

The following percentage analysis of a New Caledonian cobalt ore gives an indication of the character of the material

NEW CALEDONIA—TRANSCAUCASIA—BELGIAN CONGO 43

[6/p. 15]: Manganese dioxide, 18; cobalt oxide, 3; nickel oxide, 1.25; ferric oxide, 30; alumina, 5; silica, 8; and loss on ignition, 32.

In the period 1913–22 the only exports of cobalt ore from New Caledonia were, in 1914, 92 metric tons to England, and in 1920, 65 tons to France.

TRANSCAUCASIA

Cobalt deposits occur in the Caucasus at Dash Kessan on the east slope of the Katschkar-Tschai Valley, about 6 miles west of Elizavetopol, at an altitude of 5,500 ft.

The deposits occur in a layer of serpentine mixed with other minerals, lying between a decomposed porphyrite and a bed of magnetic iron ore.

The cobalt ore mineral is cobaltite, very irregularly distributed, with chalcopyrite and small quantities of blende, hematite and magnetite. Sometimes the ore is found in nest-like or lenticular bodies, and stringer-like segregations of ore have been observed in the gangue.

An analysis of the mineral gave the following percentages: Cobalt, 17.9; nickel, 0.22; copper, 0.21; iron, 1.44; arsenic, 35.97; insoluble, 44.26.

The deposits were mined for cobalt as long ago as 1866 by a German firm, and in 1869 it is said that 187.5 metric tons of ore were shipped to Saxony. The quantity of ore recovered in recent years has been about 15 tons per annum [45/pp. 469–70] [48A].

AFRICA

BELGIAN CONGO

The geology of the Katanga copper-belt of the Belgian Congo has been described in the Imperial Institute monograph, *Copper Ores* (p. 140). Cobalt is found in some of the copper deposits which are being mined, and is more or less recovered in the crude copper resulting from the smelting of these ores. In 1913 the Union Minière du Haut Katanga is stated to have shipped 8,064 tons of copper to Germany, which contained 2.8 to 3.25% cobalt [6/p. 1].

A portion of the ore is now smelted directly at the mines. The product contains the following percentages: Copper, 95.77; iron, 1 to 1.5; sulphur, 1 to 1.5; cobalt, 0.5. It is refined by the Société Générale Métallurgique d'Hoboken. Experiments are being carried on in Africa to produce cobalt on a commercial scale [49].

In the Star of Congo mine cobalt is found with copper in the "black ore" seam, which has a roof of hard schist and a floor of ferruginous schist. The cobalt is present as an oxide and as a phosphate of copper and cobalt [49A].

NORTH AMERICA

MEXICO

Cobalt minerals have been found in several localities in Mexico, but, with the exception of an article by Navarro [see 6/pp. 19-20] on the cobalt deposits of the State of Jalisco, little appears to have been published concerning these occurrences. Near the village of Pilhuano, canton of Ciudad Guzmán, in the southern part of Jalisco, cobalt minerals occur in veinlets cutting a large vein of magnetite associated with pyrite and pyrrhotite. The chief rock in the vicinity is described as andesite. The minerals are cobaltite, smaltite and erythrite, in small amounts, some niccolite in a gangue of greenish calcite, and a little barytes. Much ore containing 8 or 9% cobalt is said to have been mined in this district, and small shipments of ore containing 30% cobalt and 7% nickel were made from the Pihuano and Esmeralda mines.

Cobaltite is reported to occur at Iturbide in Chihuahua, at Guanaceví and in the Tamazula district, Durango; and at Cosalá in Sinaloa [50]. Small deposits of nickel-cobalt ore occur in Tepic, and a few tons of ore have been shipped, but the deposits are not large enough to warrant development [51].

Sphærocobaltite (CoCO_3) is a rare constituent of the copper-bearing beds at El Boleo, Lower California. The minerals being mined there are all secondary, but De Launay supposes that the primary minerals, existing as impregnations, were chalcopyrite, a little galena, pyrite and sulphide of cobalt [21/p. 793].

UNITED STATES

No large deposits of cobalt ore are known in the United States. For many years there has been a small production from Missouri, and from time to time there has been a small output from other states.

The lead-copper ores near Fredericktown, S.E. Missouri, carry small quantities of cobalt, which is recovered in refining the copper from these ores. The deposits have already been described in the Imperial Institute monograph, *Nickel Ores* (p. 68). The cobalt mineral is said to be linnæite, which is associated with small quantities of nickeliferous pyrrhotite, accompanying chalcopyrite in the disseminated galena deposits.

In 1900 a plant was erected by the Mine La Motte Co. for recovering cobalt oxide, and, after a small production, was closed down in 1903. In 1906, the North American Lead Co. erected a refinery at Fredericktown, and produced 2,731 lb. cobalt oxide in 1907, and 83,394 lb. in 1909, as well as some concentrate in the latter year. Operations were suspended in 1910. In 1916, the Missouri Cobalt Co. reconstructed the refinery, and production was resumed. According to C. W. Drury, the cobalt ores of Missouri are extensive, and, although low in grade, are sufficient to supply practically all the demands of the United States, which, in 1918, amounted to about 150 tons [6/p. 1]. In 1920 the Missouri Cobalt Co. recovered 102,410 lb. cobalt oxide and cobalt hydrate, valued at \$262,801 [52]. There was no production in 1921.

At Marion, Kentucky, cobalt and nickel minerals occur in association with fluorspar, but no production has been recorded.

Cobalt ore deposits are found in Grant Co., Oregon, occupying fissures in a partly-altered dolerite-porphyry. The ore-bodies vary from a few inches to several feet in width, and appear to be lenticular. The cobalt mineral is smaltite associated with chalcopyrite, malachite and bornite. Pyrrhotite, pyrite and arsenophyrite also occur, and the gangue consists of quartz and calcite. Gold and silver in appreciable amounts have been found in these ores. An analysis gave the following percentages: Cobalt, 6.34; nickel, 0.75; gold, 0.017; silver,

0-0028 [53]. Some small shipments of cobalt were made in 1905, since when production has apparently ceased. Another occurrence of cobalt ore in the same county is near Prairie City. The cobalt is found as smaltite, and is associated with pyrrhotite, chalcopyrite and gold [14/p. 964].

A quantity of 4½% cobalt ore was reported to have been opened up in 1921 in Jackson Co., Oregon.

Near Blackbird in Lemhi Co., Idaho, cobalt-nickel ore deposits occur over a considerable area, these having been traced along a belt of mineralized country 5 to 6 miles. The deposits are closely associated with gabbro dykes, and occur chiefly as lens-like bodies, although a few assume the broadly tabular form of veins. The ore-bodies also occur as bunches and disseminations along certain zones, and elsewhere are primarily of replacement origin in schist or quartzite [54].

The outcrops are usually stained by erythrite (cobalt bloom) and annabergite (nickel bloom), and contain, in addition, malachite, limonite and pyrolusite. The primary cobalt minerals appear to be cobaltite and smaltite. The nickel is probably in the form of nickeliferous pyrrhotite, and possibly niccolite. A sample taken 20 ft. across the ledge averaged about 2% cobalt. At the east end of the mine the average was 2% nickel and 1% cobalt.

In 1918, 55 short tons of concentrate, containing 17.74% cobalt (19,514 lb.) were produced from 4,000 short tons of ore [55]. Production then ceased.

Smaltite has been found in a calcite vein in granite at Gothic, Colorado, and cobalt-silver ore in a barytes vein in Los Angeles Co., California [6/p. 18].

Shipments of 6 to 28% cobalt ore were made in 1921 from the Copper Chief, High Line, and Columbia mines in the Goodsprings district of Nevada to the Shepherd Chemical Co. at Cincinnati, Ohio. It is stated that much 10% ore is available in the district. The ore is in the form of oxides and is known as heterogenite [56]. From 1869 to 1908, with the exception of the years 1905-7, when no production was recorded, the United States produced 507,102 lb. cobalt oxide. But, as already stated (*see* p. 18), no production has been recorded since 1908 [6/p. 19]. On the other hand a considerable

quantity of cobalt in the form of speiss has been shipped to the United States from Canada. From 1905 to 1913 the speiss produced in the Canadian Copper Co.'s smelter at Copper Cliff, Ontario, was all sent to the United States for refining, but since then this material has been treated at the mines. The quantities in metric tons so shipped expressed in terms of nickel, cobalt and white arsenic were as follow :

	1906.	1907.	1908.	1909.	1910.	1911.	1912.	1913.
Metallic cobalt .	4	150	210	313	157	108	101	7
Metallic nickel .	2	61	121	210	117	106	94	3
White arsenic .	—	231	427	563	382	308	216	43

Imports of cobalt products into the United States from Canada in metric tons for various fiscal years ending June 30, were as follow :

	1912.	1913.	1914.	1915.	1916.	1917.	1918.	1919.
Cobalt products, cobalt, cobalt ore and zaffier ¹	398	139	67	10	65	62	73	—
Cobalt oxide .	10	13	49	86	108	107	100	—

¹ Roasted and ground oxide ore.

SOUTH AMERICA

ARGENTINA

A cobalt ore deposit occurs at Valle Hermosa, Province of La Rioja, Argentina, which is in the form of veins in a talcose schist, near its contact with an acid igneous rock. The ore occurs on the western slope of the Sierra de Famatina, a spur of the Andes. The cobalt mineral is cobaltite, which is associated with arsenopyrite in a quartz gangue. The best ore, hand-sorted, assayed 6 to 7% cobalt, 0.5 to 2.5% nickel, 5 to 10 oz. silver and about 1 oz. gold to the ton [57/p. 49]. Up to 1904 about 300 tons of the ore had been mined and shipped to Europe, but no further production appears to have been reported [58/p. 176].

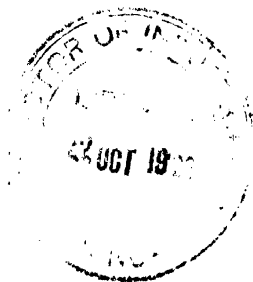
In the adjoining province of Catamarca similar veins occur, except that the cobaltite associations are pyrite and chalcopyrite instead of arsenopyrite [57/p. 49].

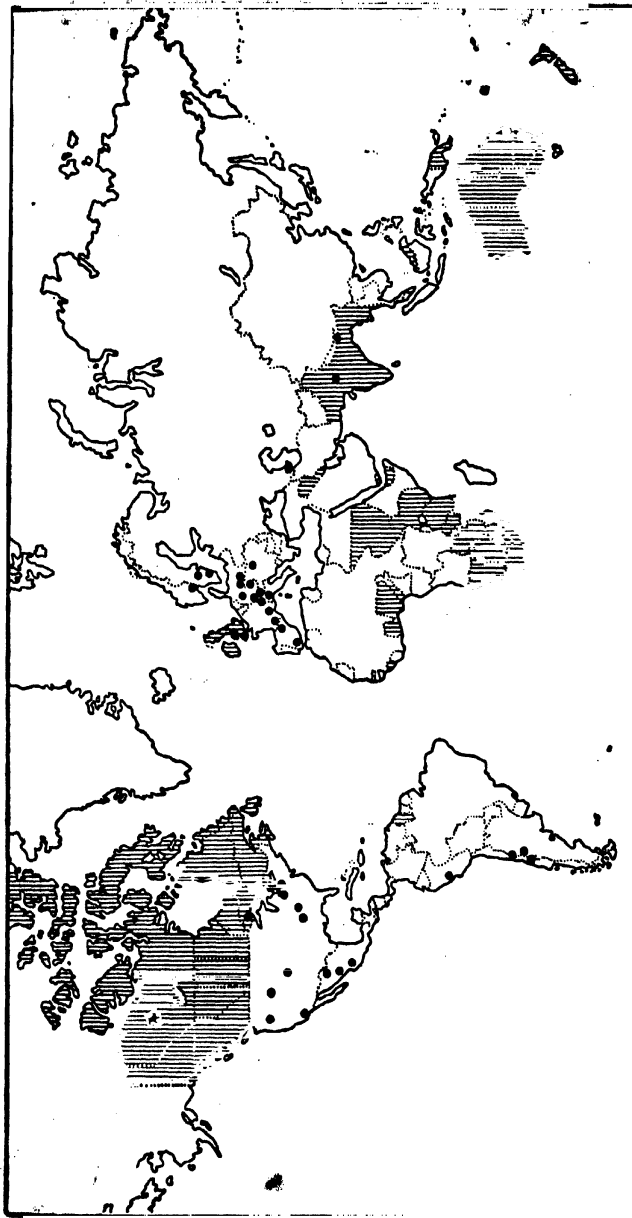
CHILE

Cobalt ore deposits occur in the provinces of Atacama, Coquimbo, and Aconcagua, Chile, from which an appreciable production took place some years ago. In 1903 the production is said to have been 284 metric tons of ore carrying 7.15% cobalt, the largest producer being the Rosa Amelia mine in the department of Frierina, Atacama [59]; but no recent production has been recorded. In this department extensive lodes, from 1 to 6½ ft. in width, occur in schist, and have been worked to a depth of 250 ft. They carry erythrite, asbolite and cobaltite. Some of the lodes carry tourmaline and a good deal of copper. The ore averages 54% cobalt. There are other mines in the Province of Atacama, that contain cobalt ores of promise [57/p. 281].

PERU

Cobalt ores occur in Peru in the nickel deposits at Rapi, province De La Mar in Ayacucho, and at Vilcabamba in Cuzco. Both occurrences are described in the Imperial Institute monograph, *Nickel Ores* (p. 73).





MAP SHOWING THE COBALT-BEARING LOCALITIES REFERRED TO IN THE TEXT.
(British Empire shaded.)

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